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Project Summary

Asphalt concrete is commonly used as the surface layer on pavements because of its convenience, low cost, and smooth ride. However, there is a significant problem with the cracking and deterioration of asphalt concrete roads. The effects or cracking in asphalt concrete have led to an increasing number of researchers using fracture mechanics to study the resistance of asphalt mixtures. Several testing methods are used for fracture testing of asphalt concrete including single-edge notched beam test, the disk-shaped compaction test, and the semicircular bend test (SCB). The SCB test will be used in this research to determine the fracture energy, the amount of energy needed to separate two surfaces, of asphalt concrete. However, there are problems with the current fracture testing methods because they create stress concentrations at the top of a rectangular notch, which forces the crack to initiate from one predetermined place. This may not accurately represent how fracturing occurs out in the field. Researchers need to find ways to isolate and measure the true fracture energy while testing.

This research will explore the fracture energy measured in a specimen using three different notch geometries: a typical rectangular notch, a circular notch, and a fatigue-cracked specimen. Researchers today know there is a problem with roads cracking and understand that what we are doing is not working, and we believe that a step towards better understanding fracture energy is by exploring notch geometries.

The Effects of Notch Geometry on Fracture Testing of Asphalt Concrete

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Introduction

Asphalt concrete is commonly used as the surface layer on pavements because of its convenience, low cost, and smooth ride (Wagoner, 2005). However, there is a significant problem with the cracking and deterioration of asphalt concrete roads. The initiation of cracking in asphalt must be better understood in order to further improve pavement design. Fracture energy is the amount of energy needed to separate two surfaces. The semicircular bend (SCB) test can be used to measure the fracture energy of asphalt concrete. Currently, this method uses a semicircular specimen with a rectangular notch in a three-point bend compression test. Using a mechanically inserted rectangular notch creates a stress concentration at the top of the notch, causing the crack to initiate from one predetermined place: either on the left or the right of the notch. Therefore, the fracture energy found from the load vs. displacement curve may not representative of the true fracture energy of the specimen. In order to better isolate the fracture energy of asphalt concrete, this research will explore the fracture energy results of using a semicircular notch, a fatigue-cracked notch, and the traditional rectangular, mechanically inserted rectangular notch.

Background and Motivation

The impact of using different notch geometries could lead to a better understanding of what initiates cracking in asphalt and where the crack will form, which will hopefully improve design methods for asphalt concrete. Even the narrowest practical mechanically inserted notch cannot simulate a natural crack well enough to provide a satisfactory measurement of fracture toughness (ASTM E399). The fracture energy of a specimen is found by dividing the area under the load vs. displacement curve by the area of the fracture face (ligament X thickness), as specified in the ASTM D7313-06 (Braham, 2007). In other words, this is the work of the fracture divided by the area of fracture. Due to the elastic behavior of asphalt (especially at high loading rates and low temperatures), there is a significant rise in the load vs. displacement curve at the beginning of the traditional SCB test, which correlates to a spike in energy before a crack forms because of the development of a cohesive zone around the notch (Wagoner, 2005). When using a rectangular notched specimen, the failure is expected to occur at the top of the notch at one of the corners, but failure can occur due to a number of variables, including misalignment of the specimen during testing or the random placement of the relatively large aggregate in the heterogeneous structure. This “forcing” of a crack to form in a specific location provides difficulty in the ability to provide accurate fracture properties. Using a circular notch like that of the Dog-Bone Direct Tension (DBDT) test improves the disadvantages of a rectangular notch by providing a known failure plane (Koh, 2009). “Failure limits of the specimen are more accurately determined from measurements directly on the failure plane with less propensity for failure due to eccentricity and effects than in specimens of uniform cross-section (Koh, 2009).” Another solution to potentially inaccurate fracture energy quantification would be the use of a fatigue crack. By fatigue cracking a specimen, a micro-crack is produced that is unaffected by the cracking procedure and should reduce the initial energy spike seen in the load vs. displacement curve, which dilutes the actual fracture energy of the formation of new surfaces.

Objective

The objective of this research is to more precisely capture the fracture energy of asphalt concrete by performing fracture tests using the traditional notch, a fatigue-cracked notch, and a semicircular notch. Since current testing procedures create a high stress concentration at the top of a rectangular notch, which then forces a crack to form at the corner and propagate through the specimen, this research will explore and compare two new types of test specimen notch geometries. One of the new geometries is a fatigue-crack that simulates the fracture tests run on steel by creating a cyclic load on the specimen in order to weaken the cohesive zone before continuing the test. This would likely measure more of a true fracture energy since the energy measured is only the crack propagation through the specimen and not the initial crack formation. The other geometry to be explored is similar to the Dog-Bone test in that the notch is a semicircle that allows the crack to form anywhere along the notch instead of at a predetermined high stress concentration. With a better understanding of the fracture energy of asphalt concrete, the future design and testing of roads will eventually lead to fewer cracks and a more sustainable infrastructure.

Materials and Methods

One traditional asphalt concrete mixture was used in this research. This mixture had a nominal maximum aggregate size of 12.5mm coming from a surface mix of a typical state highway, and a PG 64-22 asphalt binder. An air void content of 7% was targeted in order to be in the typical range targeted in field construction. The SCB test method mentioned above was used. This method called for a cylindrical specimen with a 150+-9mm diameter to be sliced into 24.7+-2mm thick plates and then each plate cut in half, as shown in Figure 1. Each cylinder was batched and compacted using the same mix design and the same gyratory compaction method. The specimens were gyratory compacted to a calculated height of 134.3mm and an average air void of 6.3% was achieved for the set of samples. Four semicircular specimens with 1" thickness were cut out of one cylindrical sample. In total, 72 samples were created, however, some cylinders were misplaced and a total of only 54 samples were tested. Tests were run using the SCB test method, specifically looking at the three different notch geometries, three testing temperatures, and two loading rates. The testing device is run using a specified loading rate, meaning the test is displacement controlled.

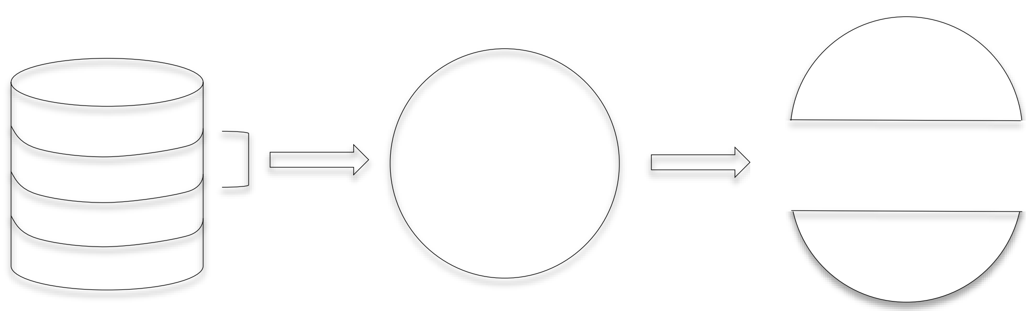
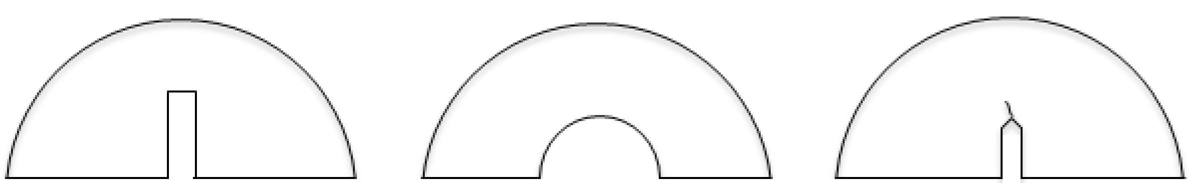


Figure 1: SCB Specimen Preparation from Asphalt Concrete Cylinder

The SCB test method consists of a closed-loop axial loading device (MTS system), a measuring device, a three-point bend test fixture, and a data acquisition system (Li, 2004). Loading rates of 0.03 and 1.0mm/minute were used in order to ensure stable crack growth conditions. Load line displacement (LLD) was measured by an external linear variable differential transformer (LVDT) for all tests in order to have consistency. LLD is measured in the direction of the load and is monitored using a clip gage placed on knife-edges that are glued 9mm apart on the bottom of the specimen at the crack mouth. However, due to the semicircular notch geometry and in order to remain consistent among all specimens, the gage was clipped onto knife-edges that were placed 9mm apart at the tip of the crack on the face of the specimen and therefore measured crack tip opening displacement (CTOD). The SCB test was run until the load dropped below 0.5kN (Li, 2004). If the load did not reach a maximum load that was above 0.5kN, the test was stopped after fifteen minutes. Each specimen was kept at room temperature or in the temperature state at which it would be eventually tested. This allows for better isolation of the actual fracture energy of the specimen without dissipated energy. Temperature was controlled within 1˚C of the desired value; each test was run at three different temperatures: +24˚C, 0˚C, and -24˚C with the three notch geometries. A full factorial analysis of the experimental matrix shown in Table 1 was performed with two to four replicates of each. The three different notch geometries that were tested are shown in Figure 2 below.

Table 1. Experimental Matrix

Variables	Values
Notch Geometry	Rectangular, Fatigue-crack, Semicircle
Loading Rate (mm/min)	0.03, 1.0
Test Temperature (°C)	-24, 0, 24



a) Rectangular Notch b) Semicircular Notch c) Fatigue-cracked Notch

Figure 2: Three Notch Geometries

The first test that was executed was run using the standard rectangular notch according to AASHTO TP105-13 standard: Determining the Fracture Energy of Asphalt Mixtures using the Semicircular Bend Geometry. For these tests, the rectangular 15+-5mm long notch, no wider than 1.5mm was cut along the axis of symmetry as shown in Figure 2a. Due to misplacing and breaking some samples, only two replicates of each were tested. During the testing of specimens at the warmest temperature (24°C) and the slowest loading rate (0.03 mm/min), the load never reached a peak load above 0.5 kN, so the decision was made to stop the test consistently after 15 minutes. Fracture energy in J/mˆ2 was calculated from the results and represented by the area under a plot of a load vs. displacement (CTOD) curve.

The next test was using a semicircular notch similar to that of the research done by C. Koh in 2009, using Dog-Bone geometry. The notch has a 1" diameter, oriented as shown in Figure 2b. The advantages of this geometry are that the failure plane is known and the stress concentrations near the loading head have minimal effects on the test results. In addition, the crack was able to choose the most natural path of formation and was not forced into one of two locations as is done with the traditional rectangular geometry. Therefore this test was a measure of crack initiation and propagation. The SCB test was run according to AASHTO TP105-13 for all specimens with this geometry.

The ASTM E399 Standard Test Method describes the specimen for obtaining the plane-strain fracture toughness of metallic specimens. The ASTM E399 was used as a starting point for the testing of the third geometry shown in Figure 2c. Fatigue cracking a specimen allows for the cohesive zone at the top of the notch to be at a minimum. In this method, it is assumed that the fracture energy is size-independent and is constant along the crack path over the entire fracture area. The methods from ASTM E399 and AASHTO TP105-13 were combined in order to perform the SCB test on a fatigue cracked asphalt concrete specimen. This test was very dependent on human control. Five increments were created based on the anticipated maximum load. The loads had to be carefully watched and the test was manually stopped at each increment until the load visibly reached a maximum. Once the maximum was reached, the test was allowed to continue running according to the original ASTM specifications. Several attempts were made to create a program on the MTS machine that would stop the test at each increment, but none were successful. Ideally, the loads applied to the specimen should have been very fast and cyclic, however, the person had to run over and release the load each time the test was stopped. There was no visible crack in the specimen before the peak load was reached. A typical plot of load vs. displacement for an entire process of a fatigue-cracked sample can be seen below in Figure 3. In this plot, one can see that the specimen was loaded and then unloaded at 0.6kN, 1.1kN, 1.3kN, 1.4kN, then hit a peak of 1.6kN and was allowed to continue running. Once the specimen had been fatigue cracked, the final run of the test therefore measured only crack propagation since the cohesive zone was already weakened. Results from all three tests were analyzed and compared to each other in order to determine if the fracture energy of the specimens was more precisely captured.

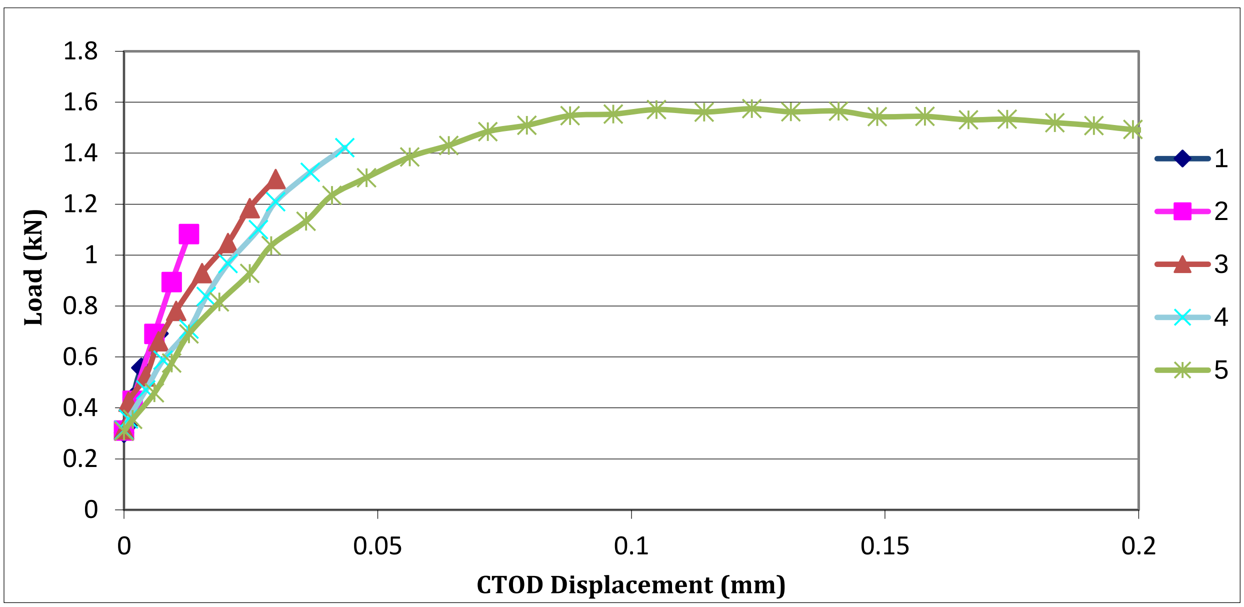


Figure 3. Fatigue-crack test showing 5 increments

Results

The following Figures 4 and 5 show the results from testing. Figures 4a-c show the typical load vs. displacement curve at a loading rate of 1.0 mm/min in order to compare each notch geometry at each temperature.

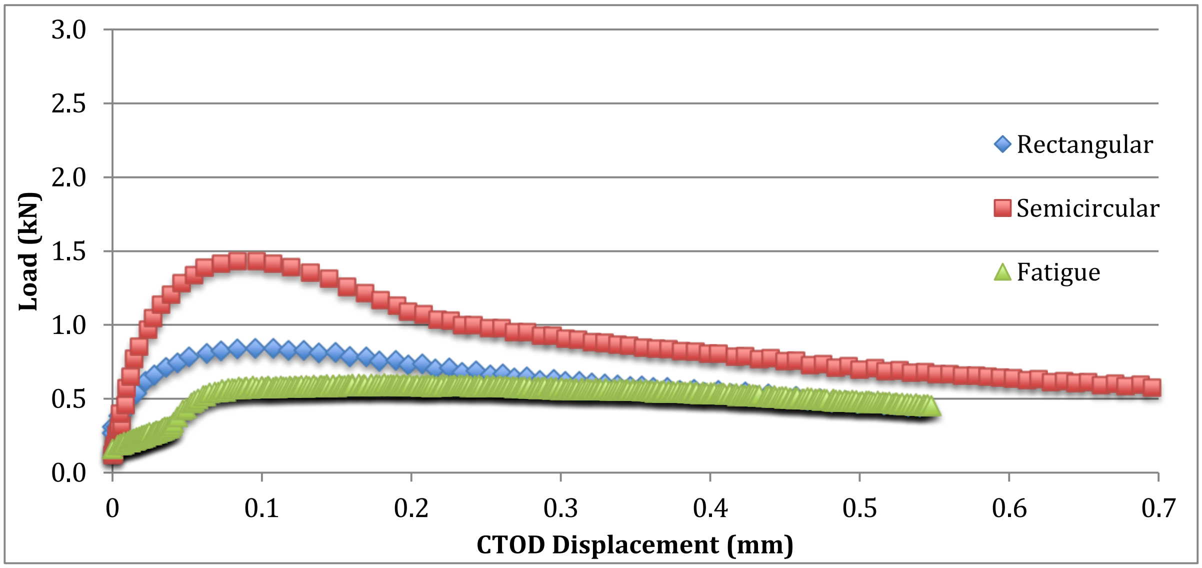


Figure 4a. Load vs. Displacement at 24°C

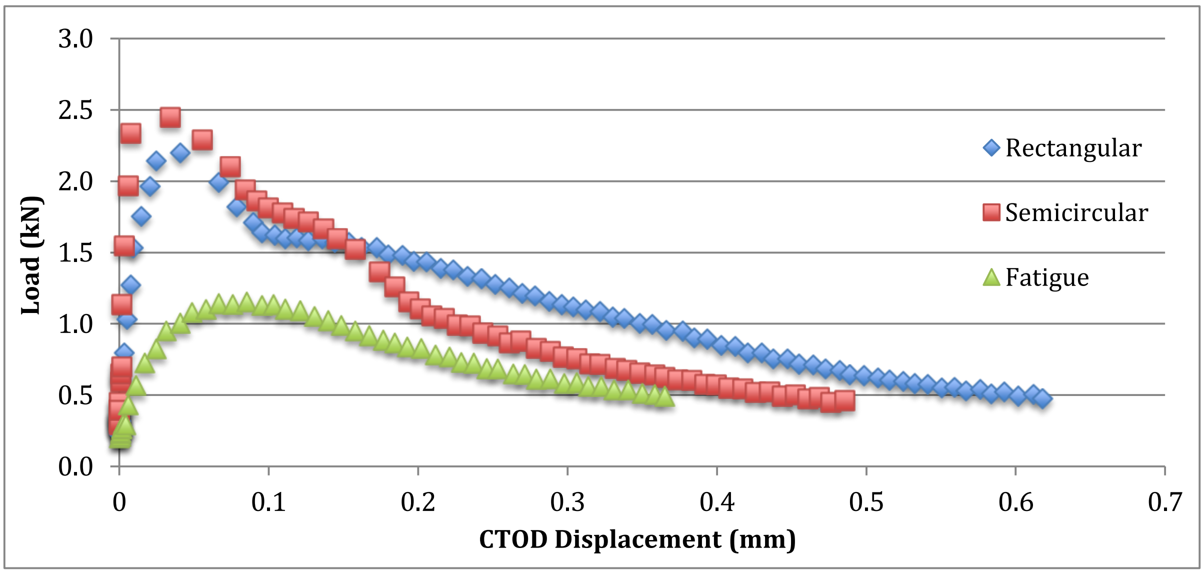


Figure 4b. Load vs. Displacement at 0°C

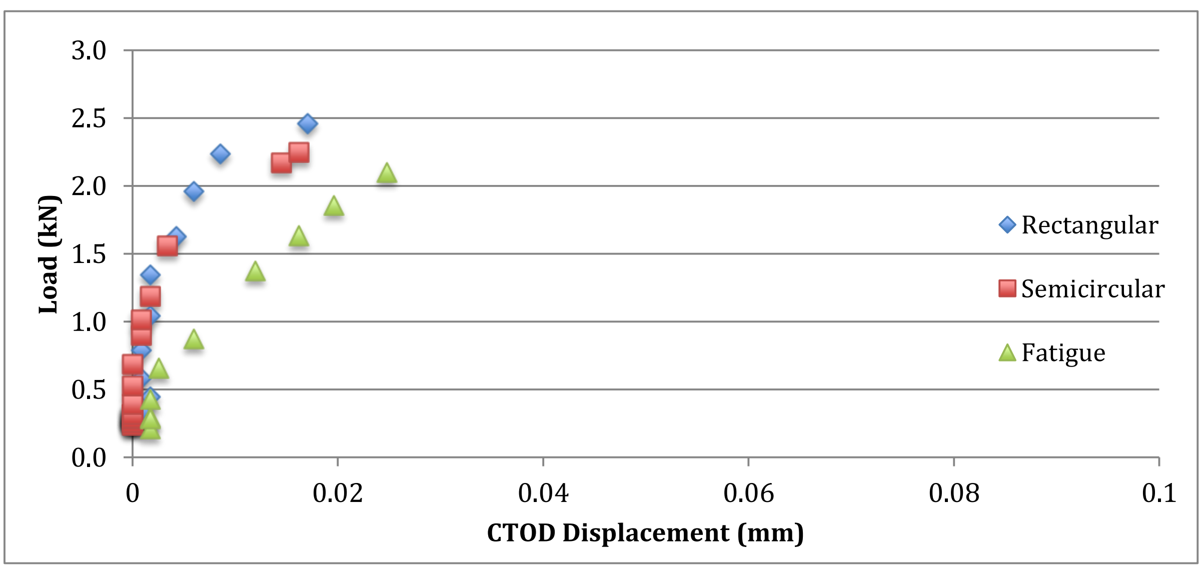


Figure 4c. Load vs. Displacement at -24°C

For each of the different notch geometries and loading combinations, the fracture energy was calculated using the area under the load vs. displacement curve. The results are shown in Figures 5a & b with one standard deviation of error. If standard deviation is zero, only one sample was tested.

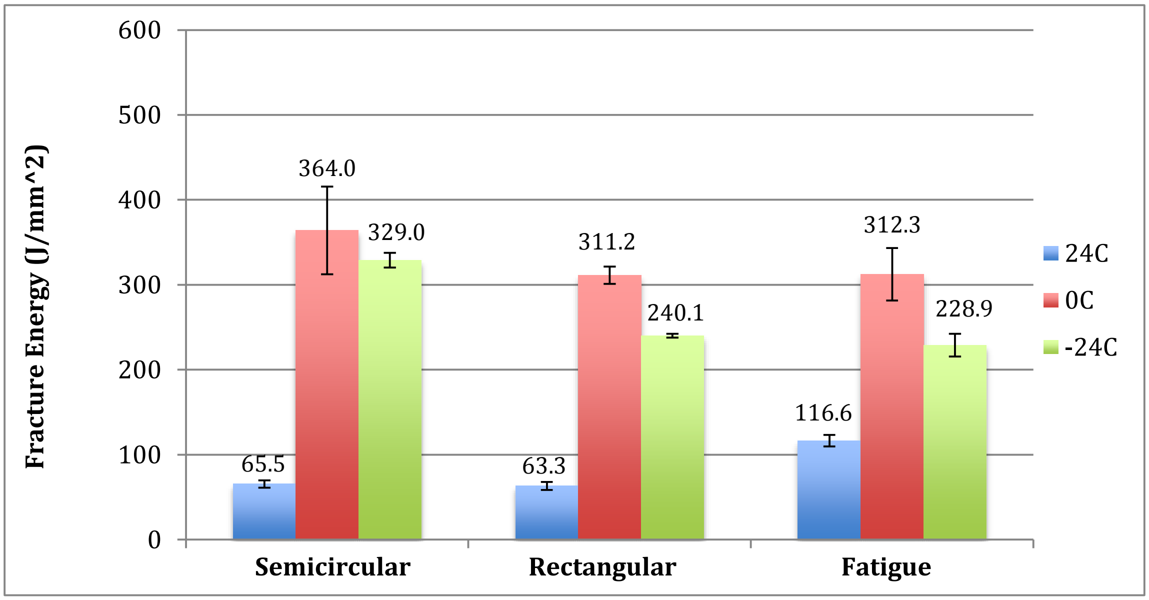


Figure 5a. Fracture energy at 0.03 mm/min loading rate

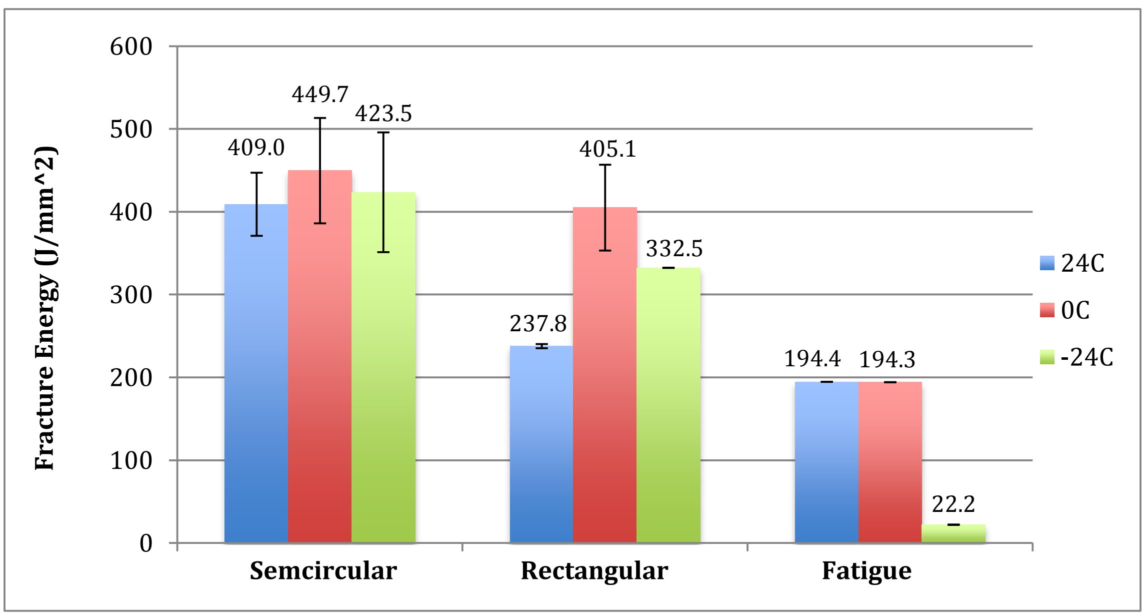


Figure 5b. Fracture energy at 1.0 mm/min loading rate

From a comparison of notch geometry in Figures 4 and 5, there are noticeable trends in fracture energy. Semicircular notches consistently measured a greater fracture energy than that of the standard rectangular notches, and the fatigue notches consistently measured a lower fracture energy than that of the rectangular notch. It should be noted that when testing at the warmest temperature and the slow loading rate, the material showed no significant peak load or visible cracking; this test behaved more like a creep test and therefore is not a valid measure of fracture energy. Conversely, when testing at the lowest temperature and highest loading rate, the material showed a very brittle failure and split immediately when the peak load was reached. This also is not a valid measure of fracture energy. The elastic behavior in the high temperatures and the brittle behavior in the cold temperatures is noticeable in the graphs. From examining and comparing the behavior of each specimen at the various temperatures as shown above in Figures 4a-c, it can also be noted that in general, the colder the temperature the higher the peak load.

The trends seen in Figures 5a & b are to be expected. The high concentration of stress formed in a rectangular notch would lead to a forced initiation of a crack at the corners beginning to propagate through the sample and therefore, less energy required to separate the two surfaces. Whereas, for a semicircular notch, the crack is most likely to form in the center of the sample but has the freedom to form around a possible large aggregate if it is in the way. Because of this, there was a greater amount of energy needed to separate the surfaces using a semicircular notch. Similarly, in a fatigue-cracked sample, the cohesive zone was weakened if not diminished completely which created a tiny non-visible crack in the sample and the final test measured solely the crack propagation. It is reasonable for this measure of fracture energy to be less than that found in the other geometries. Additionally, for all situations, the greatest fracture energy was measured at a temperature of 0°C and the lowest fracture energy was measured at a temperature of 24°C.

Since fracture energy is a fundamental property of a material, it should be a measure of the energy required to separate two surfaces. This indicates that the fatigue cracking method would be most appropriate to measure fracture energy, as there is no cohesive zone. However, pavement cracking does involve crack initiation and therefore does involve a cohesive zone. Therefore in this case, the semicircular notch, in theory, would be the best test method in order to measure crack initiation and propagation.

Conclusions

This research was an exploration of ways to measure fracture energy in order to determine a more accurate representation of the true fracture energy. Based on the amount of cracking occurring in pavements, it is possible that current test methods may be an underestimation of the amount of energy required to actually separate two surfaces. This research explored two new forms of testing by changing the geometry of the test specimen. One new geometry was a semicircular notch which was specifically intended to measure crack initiation and propagation. The other geometry was a fatigue cracked notch which was intended to measure solely crack propagation. Both new methods were then compared to the standard test method used today. In total, three different notch geometries were tested and analyzed.

Tests were performed using the SCB test based on mainly AASHTO TP105-13 with some modifications taken from ASTM E399 in order to account for the new fatigue cracked geometry. Instead of measuring displacement during loading at the crack mouth, it was measured at the crack tip on the face of the specimen for all samples. Three temperatures, three notch geometries, and two loading rates were used for testing, with between two and four replicates of each.

Based on results from testing, it is clear that the semicircular notch was in fact a measure of both crack initiation and propagation and the fatigue cracked notch was able to measure solely crack propagation. Because of this, the fracture energy measured with the semicircular notch was greater than that of the standard rectangular notch and the fracture energy measured with fatigue cracked samples was less than that of the standard rectangular notch. In theory, the fracture energy is a material property, it should be a measure of solely the crack propagation through the specimen. Therefore, the best test to measure this would be the fatigue cracked method. If the intent is to measure both crack initiation and propagation, then the semicircular notch method would be best.

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